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Advances in Fiber Lasers
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Division of Engineering, Brown University,

Providence, RI 02912

T.F. Morse, Professor of Engineering

Introduction

The Laboratory for Lightwave Technology with support from AFOSR, Physics, has continued its efforts to develop new techniques for the processing of photonic materials, in particular optical fibers, and to develop novel sensors for various defense applications. In particular, we have devoted much of the time of this contract toward improvements in optical fiber lasers and toward gathering experience to improve our program in high power, cladding pumped optical fiber lasers. The Laboratory for Lightwave Technology has served as a focus for the fabrication of specialty fibers not only for industry, but for various governmental laboratories such as the Phillips Laboratory, and the Lawrence Livermore Laboratory. In addition, through cooperative research with faculty at other universities, we have been in a position to supply novel rare earth doped fiber lasers. We were able to show that by doping a silica fiber with Nd and Er ions, and by simultaneously pumping with 800 nm radiation (to invert the Nd ions) and with 980 nm radiation (to invert the Er ions) it was possible to obtain lasing at both 1,060 nm and 1537 nm. More recent work has investigated the Tm and Er systems. Since there is a resonance transfer between an upper state of Tm (that can be pumped at 790 nm) and Er, it was possible to pump the Tm at 790 and, by lattice energy exchange, to obtain an inversion in the Er that resulted in lasing at 1538 nm. Indeed, by proper adjustment of

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Dr T. F. Morse

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Division of Engineering
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13. ABSTRACT *(Maximum 200 words)*

Most of the time of this contract has been devoted toward improvements in optical fiber lasers and toward gathering experience to improve our program in high power, cladding pumped optical fiber lasers. The Laboratory for Lightwave Technology has served as a focus for the fabrication of specialty fibers not only for industry, but for various governmental laboratories such as the Phillips Laboratory, and the Lawrence Livermore Laboratory. In addition, through cooperative research with faculty at other universities, we have been in a position to supply novel rare earth doped fiber lasers. We were able to show that by doping a silica fiber with Nd and Er ions, and by simultaneously pumping with 800 nm radiation (to invert the Nd ions) and with 980 nm radiation (to invert the Er ions) it was possible to obtain lasing at both 1,060 nm and 1537 nm.

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system parameters, it was indeed possible to pump this system at 790 nm and obtain lasing simultaneously at 1,857 nm and 1,537 nm. We believe that this is the first time that this has been achieved.

Temperature Tuning of Fiber Lasers

We have previously described how an aerosol technique developed in our laboratory has proved to be particularly useful for co-doping optical fiber lasers. The tuning of fiber lasers is important not only for telecommunications, but for spectroscopic and sensing applications, as well as for the creation of efficient optical delay lines for phased array applications. We have reported, under AFOSR support, a new technique by which it is possible to tune optical fibers over a wide band width. This will be of particular importance for some techniques we have developed for intra-cavity fiber laser spectroscopy.

It is well known that a 2 x 2 fused taper coupler can function as a loop mirror for an optical fiber, either in a ring or a linear configuration. By making a 2 x 2 coupler that is "overcoupled", i.e., many optical cycles during the fabrication process, we obtain what we call a HOCC (Highly Over-Coupled Coupler). If such a coupler is made so that its spectral output has a monotonic decrease over the bandwidth of a fiber laser, and if this device is used as the output coupler, then, as the fiber is strained, or, more easily, temperature tuned, the reflectivity of the loop mirror changes. For a given fiber doping and geometry, if we change the reflectivity of the output coupler, the lasing wavelength will shift. Bu attaching a loop mirror fabricated from a HOCC to a small Peltier plate, we have been able to temperature tune the wavelength of both linear fiber lasers, and fiber ring lasers. We have continuously tuned an Er laser over the total gain band width from 1,527-1,572 nm with a temperature increase of only 20 degrees centigrade. In addition, as opposed to other techniques for fiber tuning (not using a bulk element such as an intra-cavity grating), the tuning has been continuous. We have also been able to tune the Tm system over 80 nm, and, using different HOCCs as output couplers, over 150 nm total.

This is of importance for some spectroscopic applications, and for possible optical delay lines, if this tuning can be accomplished rapidly enough. Thermal change of the reflectivity of the output coupler, however, can not be rapid enough for an optical delay line, and we have performed the following experiments. If a 2 x 2 Mach Zehnder switch in lithium niobate is used to replace the functionality of the loop mirror, and if the two output arms are connected, we have a similar situation. To overcome losses (approximately 4 dB/pass) in the lithium niobate, the output arms are made of erbium fiber and pumped by 980 nm. We attempted this experiment with lithium niobate devices obtained from Lucent Technologies, and from a 1.3 device fabricated by Uniphase and lent to us by Prof. K. Bergman of Princeton. Unfortunately, the Mach Zehnder configuration was not wavelength dispersive, since this was a balanced Mach Zehnder, designed to give a flat response with respect to wavelength. This is not unexpected, since these devices were for telecommunications applications, and the switching should be relatively wavelength independent. We have, however, located an unbalanced Mach Zehnder lithium niobate device at Tetra-Tech Corporation in California, and they will lend us this. This device does have wavelength dispersive characteristics similar to our loop mirror experiments. We believe that there is a reasonable chance of obtaining tuning over many tens of nm in the erbium system. The switching time of the lithium niobate device will be less than a nanosecond, so the equilibration time will be determined by the time it takes for the laser to "ring down" to the new wavelength. We believe that we can make the total laser length less than a meter, and if 50 round trip times is the order needed to achieve equilibrium at the new switched wavelength, then we should be able to switch to a new, and significantly different laser wavelength in less than a microsecond.

By putting a changed wavelength into a dispersive, but not necessarily loss, fiber, we have an optical delay line. If this can be switched in a microsecond or less, this has significant implications for phased array radar. We hope to continue these experiments in the near future when we obtain the unbalanced Mach Zehnder device (Uniphase) from Tetratech.

Fiber Laser Intra-Cavity Spectroscopy (FLICS)

It is well known that when an absorber is placed within a laser cavity it can spoil the gain and give rise to a significant loss of laser power, or an extinguishing of the lasing itself. This concept has been used in the laboratory for the measurement of extremely small amounts of absorber. We have extended this concept to compact fiber lasers. Any absorber can be measured that has an absorption signature under the gain bandwidth of the fiber laser. Of particular interest is the erbium fiber laser, with a tuning range of 1,527 nm to 1,573 nm, and the thulium fiber laser, which exhibits gain between 1,700 and 2,000 nm. Although this is a "narrow band" instrument, there are many important gases to be detected in these wavelength regions. In particular, the sensitivity of the technique is such that overtones may be detected.

We have done initial model experiments with the erbium fiber laser, and we have strain tuned a Bragg grating at 1,533 nm to detect the presence of acetylene, which absorbs in this wavelength region. The line separation of the acetylene is less than 1 nm. If the laser is tuned between these lines, there is no absorption, and if the laser is tuned to an acetylene line, there is a change in intensity of 50 dBm. The problem with such measurements is that there is a relatively large amount of noise in the system. Nevertheless, even this simple detection technique can be used to note the presence of a new class of freon replacements that substitute for halon flame retardants. These are contemplated for use in the suppression of fires in aircraft. At the present time, the detection of the presence of such gases depends upon diffusion through a membrane, and the response time of such detection is many tens of milliseconds. The use of such a technique would reduce this time to a few microseconds.

One of the techniques that can be used to increase detection sensitivity and reduce noise is that of Balanced Ratiometric Detection. In this concept, the lasing signal is split. One part of the signal passes through the absorber, and one part does not. The two signals are sent into the BRD and their difference is electronically detected. Since the noise in the two signals is identical, the sensitivity of detection is increased significantly. We have used this technique with a Tm fiber laser to detectd the third overtone of NO in the 1,800 nm regime. This is a wavelength region in which there are no convenient diode sources available. In addition, the tunability of such diode sources is limited to a few nm.

Since intra cavity spectroscopy holds the promise of great sensitivity, and, in fiber form, in a compact configuration, we have made several attempts to make this process compatible with a two beam system. This would allow BRD techniques to reduce noise. First we placed a beamsplitter in front of the absorption cell to direct 1/2 of the cavity light toward another mirror. Thus, we attempted to create a cavity with two independent outputs, but with the same noise. This seemed attractive, but the experiment failed. Although it appeared that there were two cavities, when one cavity was blocked off, the other cavity stopped lasing, and vice versa. Thus, the cavities were not independent, and a more complex "Y" shaped cavity was formed. The next modification to this concept was the following. The polarization of the fiber gain medium was controlled by "polarization" paddles, or loops, so that the polarization vector impinged on a polarizing beam splitter at 45 degrees. Thus, "x" polarization went straight through the beam splitter and through the absorption cell, and "y" polarization exited the beam splitter at right angles and impinged upon an broad band output coupler. This resulted in two laser outputs, "x" and "y" polarization; however, the noise in each of the laser signals was identical. If the output of each of the polarizations was sent into a detector, the signal was extremely noisy. When no absorber was placed in the cell, and the BRD was used to subtract the laser output of different polarizations, the response was extremely flat. We have increased the sensitivity of detection over the initial application of FLICS by three orders of magnitude. There are sill some problems with phase noise in the system, since the bulk optical components used in our experiments were not properly coated. We have recently received an all-fiber polarization beam splitter from K.O. Hill, of the Defense Research Group in Ottawa, Canada, and further experiments are in progress.

High Power Cladding Pumped Optical Fiber Lasers

The brightness theorem states that focusing light from one optical medium to another, the product of area and numerical aperture must be constant. For this reason, it is not possible to focus the high output powers available from multiple stripe diodes into the core of a single mode optical fiber. However, by focusing this radiation into a multimode guiding structure in the center of which is a single mode rare earth doped core, the light will, over some distance, interact with the core and be absorbed. Since all of the light focused into the multimode structure will not consist solely of meridional rays, it is necessary to break the symmetry of the structure to prevent helical rays from spiraling around the core. The Polaroid Corporation has patented the concept of a rectangular multimode structure surrounded by a low index plastic, and a single mode core in the center. A recent post-deadline paper at CLEO from SDL (they have purchased the Polaroid fiber facility) has produced 110 W of CW radiation from a single mode Yb core.

In an effort to develop an all-glass cladding pumped fiber later, we have concentrated upon two designs. The first of which results in a numerical aperture approaching 1.0. This is achieved in the following manner. We take a typical rare earth doped optical fiber preform, 14 mm in diameter, and we then wrap this with a 2 mm low index glass rod (obtained from the glass institute in St. Petersburg). The pitch of this helical wrap is also approximately two mm. This "candy cane" is then sleeved with a quartz tube to yield and all-glass optical fiber.

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